Copenhagen '12

C041

Utilizing SMTI to Characterize the Behavior of Fractures During Hydraulic Stimulation of Naturally Fractured Reservoirs

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SUMMARY

Through seismic moment tensor inversion (SMTI) of microseismic events related to stimulation in a shale gas play utilizing well-conditioned geophone arrays, we have been able to define a complex three dimensional discrete fracture network consisting of sub-horizontal and sub-vertical fractures. Geologic data from the sites provided corroborative evidence that the moment tensor derived fracture orientations are in-line with the outcrop defined discrete fracture network, suggesting that in shale gas plays the preferred mode of failure during stimulations is the re-activation of pre-existing fractures and joints. It can be further suggested that the presence of sub-horizontal fractures are locally responsible for the transfer of stress resulting in failure along sub-vertical fractures and in the development of a well connect fracture network, required for effective proppant transport. The observed modes of failure can generally be categorized as being dominated by mixed–mode failures, representative of shear-dilatational failures. The opening–closure behavior of observed events, particularly for the sub-horizontal fractures can be related to surface roughness and the presence of asperities. The nature of fracturing appears to be fractal, following a power law distribution. It suggests that when stress levels are sufficiently high, fractures with similar orientations coalesce and develop longer fractures.

Introduction

In general, it is considered that fractures grow irregularly in a stress field that is perturbed by a hydraulic fracture injection. It is also considered that structural weaknesses in the rock such as pre-existing fractures and naturally occurring laminations commonly found in, for example, shale-gas reservoirs, can be conduits for fracturing during stimulation and active pathways for fluid flow (e.g., Reine and Dunphy, 2011). We postulate that local stress perturbations through stress transfer allow for fractures to initiate failure along pre-existing fracture sets. The mode of failure or failure mechanism may then be directly related to the deviatoric stress levels acting on the fracture, the principal stress orientations, and the irregularities or asperities of the fracture surfaces themselves (roughness). Under these varying conditions, shear slip can occur along pre-existing fracture sets as can shear dilatational behavior for failing surfaces with higher degrees of roughness, or dilatational behavior when injection rates are high and injection pressures are large (e.g., Murphy and Fehler, 1986). In a hydraulic fracturing operation it is likely that the entire range of these behaviors are possible and can occur in naturally fractured or jointed reservoirs. The interaction of these fractures leads to a complex pattern of fluid flow and fracture interconnectivity that play a role in whether effective proppant transport is achieved.

Microseismic monitoring offers insight into the stress conditions under which failures occur leading to a better understanding of fracture geometries and the development or mobilization of a fracture network. The waveforms of individual microseismic events are reflective of the localized stress strain conditions at the source and can be inverted to identify the underlying components of failure (Baig and Urbancic, 2010). Seismic Moment Tensor Inversion (SMTI) analysis yields information on the modes of fracturing and through the decomposition of the inversion results and using source-type diagrams (Hudson, 1989) mechanisms consistent with cracks opening or closing, volumetric and pure-shear failures, or mixed-mode failures are identified. Consideration of these different source types can be used to resolve the fracture planes in relation to the strain equivalent principal axes of the moment tensor (i.e. pressure, P, and tension, T). Shear dominated events can be grouped using a nearest neighbor approach and the (best-fitting) local stress field determined and used to define the likely fracture orientations of individual events (Gephart and Forsyth, 1984). Similarly, it is considered that fracture plane for failures exhibiting significant opening components of failure are normal to the T axis whereas closure dominated events the fracture are normal to the P axis. Fracture lengths for opening – closure dominated events can be approximated by the tensional equivalent with greatest displacement at the center of the fracture (Walter and Brune, 1994) whereas the shear failure equivalent assumes displacement over the entire fracture surface (Brune, 1970, 1971). Utilizing these models, individual fracture lengths are estimated based on the calculated source radii. The spatial – temporal distribution of fractures from moment tensor analysis defines the discrete fracture network and the growth of the overall volume of fractures.

Here, we examine microseismicity recorded utilizing a multi-well multi-array (geophone) configuration for stimulations in shale gas reservoirs in North America. Well-constrained moment tensors derived for individual events are used to describe the failure behaviour of individual events and further to identify fracture orientations that define the localized discrete fracture network. Supporting geologic data is used to corroborate the microseismic data. Based on these observations, we argue that the growth of hydraulic fracture stilumlations in reservoirs with brittle high rock strength is dominated by a stress transfer resulting in the re-activation of pre-existing fracture or joint networks and that failure is generally mixed-mode in behavior.

Analysis

In this paper we examined events recorded during stimulation of a single stage in the Horn River shale-gas reservoir in Northeastern British Columbia, Canada. Microseismic monitoring consisted of three arrays of twelve to twenty triaxial sensors in deviated wells in the vicinity of the treatment well. This allowed for general solution moment tensors to be robustly calculated. The events shown in the Source-Type plot of Figure 1 are dominated by tensile enriched crack opening and closure behavior.

Individually, events include shear components of failure, generally suggesting that failures can be generally considered as mixed - mode shear dilatational failures. In Figure 2, we have identified the fracture orientations based on the decomposition of the moment tensor results. Spataillly, we identify a complex three-dimensional discrete fracture network that is dominated by closure events to the southwest and crack-opening behavior to the northeast. The overall fracture growth is in the regional principal horizontal stress orientation. Sub-vertical fractures are principally oriented within 30 to 35 degrees from the maximum horizontal stress direction (northeast). The region to the southwest of the treatment well appears to be dominated by sub-horizontal closure events. The fracture dimensions also suggest that inter-connectivity for the fractures to the southwest is poor in contrast to the observed distribution of fractures in the northeast. The complexity of interaction between fractures suggests that the process of overall fracture development needs to consider their role in fracture propagation and propant transport.

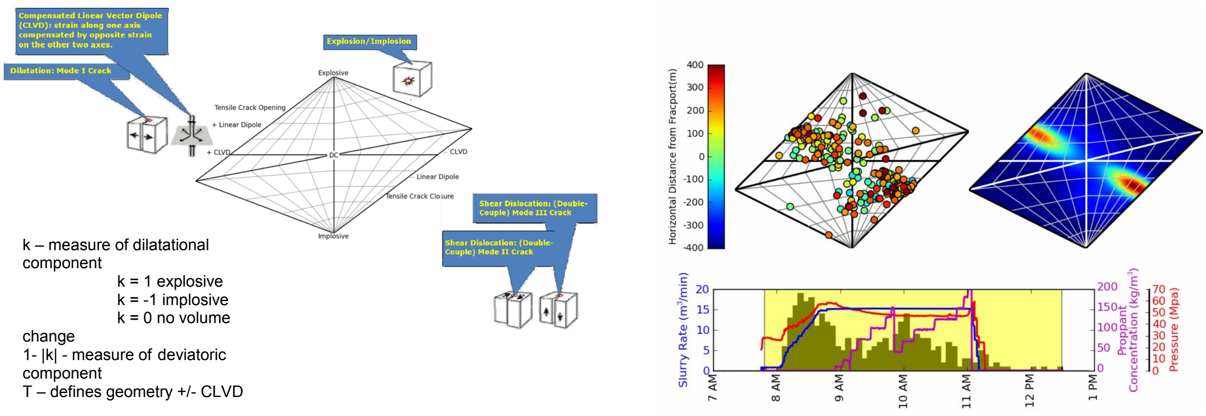

Figure 1 *Source-Type Hudson Plot outlining the different modes of failure (left) and with the moment tensor results (right). Also shown is the stimulation engineering data. Individual events on the Source-Type plot are color-coded based on relative position from the frac initiation point.*

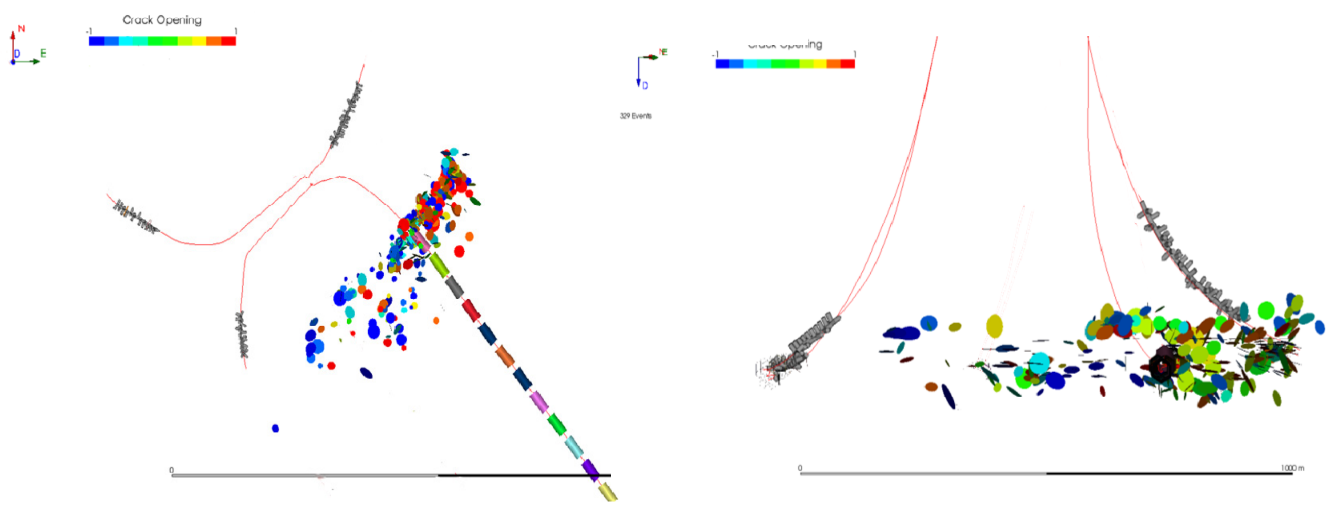

Figure 2 *MT derived fractures color coded by the opening component of the failure, where cool colors represent crack closure dominated events and warm colors are crack opening dominated events. Dimensions are plotted as circles. In plan view (left) sub-vertical fractures appear as ellipses and circles in depth view (right).*

The observed fracture complexity should not come as a surprise. In examining outcrop data from the region (Figure 3), the observed fractures define a pre-existing fracture network that consists of sub-vertical and sub-horizontal fractures of varying length scale and inter-connectivity. The image log data also show both open and healed pre-existing fractures. Both observations mimic the moment tensor derived results, which show the same level of fracture complexity and variability in fracture length. Outcrop measured fracture orientations, as shown in the Rosette diagram, although variable show two dominant orientations, to the northeast and more or less north - south. With the current stress field, it appears the northeast-southwest fracture set originated during a different episodic period than the north-south fractures, which more closely resemble the observed moment tensor fracture orientations. It further suggests that either the northeast-southwest fracture set is healed or local stress perturbations (magnitude) related to the stimulation are not sufficient to induce movement of the northeast-southwest fracture set. As shown in the outcrop measurements, individual sub-vertical fracture lengths are not necccessarily bound by individual bedding layers but can coalesce and result in composite fractures with length scales of m's. In Figure 4, we show that the moment tensor source radii follow a power law distribution. The resulting fracture lengths vary from approximately 10m to about 30m, suggesting that the coalescence of individual fractures is an on-going process and is fractal in behavior.

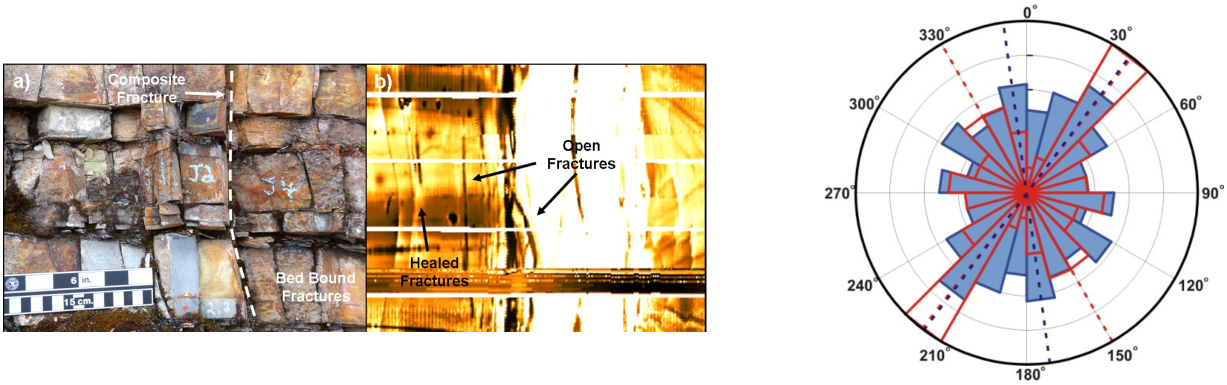

Figure 3 *Outcrop (left), image log (middle), and rosette data (right) from a nearby site (after Reine and Dunphy, 2011).*

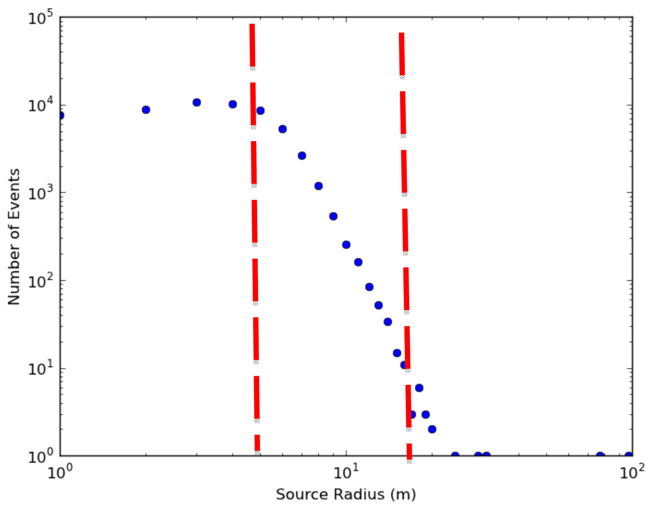

Figure 4 *Power law distribution of moment tensor derived source radii of fracture. Fracture lengths are double the source radii.*

Summary

Through seismic moment tensor inversion (SMTI) of microseismic events related to stimulation in a shale gas play utilizing well-conditioned geophone arrays, we have been able to define a complex three dimensional discrete fracture network consisting of sub-horizontal and sub-vertical fractures. Geologic data from the sites provided corroborative evidence that the moment tensor derived fracture orientations are in-line with the outcrop defined discrete fracture network, suggesting that in shale gas plays the preferred mode of failure during stimulations is the re-activation of pre-existing fractures and joints. It can be further suggested that the presence of sub-horizontal fractures are locally responsible for the transfer of stress resulting in failure along sub-vertical fractures and in the development of a well connect fracture network, required for effective proppant transport. The observed modes of failure can generally be categorized as being dominated by mixed – mode failures, representative of shear-dilatational failures. The opening – closure behavior of observed events, particularly for the sub-horizontal fractures can be related to surface roughness and the presence of asperities. The nature of fracturing appears to be fractal, following a power law distribution. It suggests that when stress levels are sufficiently high, fractures with similar orientations coalesce and develop longer fractures. Utilizing the defined pre-existing fracture network, failure modes, and power law distribution, a description of fracture network development is defined and can be utilized to constrain and validate predictive reservoir models.

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